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FARNBOROUGH, HANTS

TECHNICAL NOTE No: R.P.D.30

SOME CONSIDERATIONS RELATING TO COMBUSTION IN ROCKET MOTORS

by

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U.D.C. No. 621.455.05

10 Technical Note No. R.P.D.30

6 March, 1950.

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Some Considerations Relating to Combustion in Rocket Motors 4

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SUMMARY

An account is given of some of the problems associated with combustion in rocket motors and it is shown that the improvements in rocket motor performance which may result from a greater knowledge of the combustion process are considerable. Suggestions are made for tackling some of the problems involved.

1. Rocket motors
2. Combustion

I Maxwell, W. R.

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1 Introduction

Scattered throughout the relevant literature there are many isolated statements on the various aspects of combustion in rocket motors; a few of the subjects involved, e.g. atomization of the propellants, have been studied in some detail but there are large gaps of almost unexplored territory. There are few well established facts concerning the processes taking place in the combustion chamber which can be used in designing rocket motors, and motors are normally designed on a basis of past experience and common sense. It is the purpose of research to provide the necessary basic information for the rational design of rocket motors. This note has been written in order to set forth the present knowledge on the subject, as far as known to the author, to point out the kind and importance of the improvements which can be expected, and to indicate lines of research which are likely to lead to improved performance. It is fundamentally concerned only with the processes associated with combustion or factors which may influence these processes, e.g. the shape of the combustion chamber, although attention is sometimes drawn to other subjects which may be influenced by the combustion processes, e.g. heat transfer to the walls.

2 The effect of combustion efficiency on weapon performance

An obvious question to ask of any research of the type with which we are concerned is whether the improvements likely to be achieved are worth the effort expended. The general aim of combustion research in rockets is to achieve as complete combustion of the propellants as possible in as small a space as possible. In addition a more complete knowledge of the combustion processes should permit the use of certain fuels which may normally be difficult to burn. If combustion is complete and the expansion nozzle is well designed then the measured specific impulse of the system should be very close to the calculated specific impulse. Most current motor designs produce specific impulses which are 85 - 95% of the theoretical value (calculated as in footnote*), i.e. there is a loss of specific impulse of 5 - 15%. The nozzle losses are small, probably less than 4% for motors of appreciable size[1,2,3], so it is clear that a good deal of this loss must often be due to inefficiency of combustion. It seems likely that an improvement in combustion efficiency equivalent to about 5% increase in specific impulse may be achieved in many current rocket motors (see, for example, reference 3). This may seem rather small but the following examples show that it is important.

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* Footnote: If in the method of calculating the specific impulse it is assumed that chemical equilibrium is maintained during expansion and there is no vibrational lag in the specific heats then even if combustion in the chamber is complete and nozzle losses are negligible the measured specific impulse is always likely to be slightly less than the calculated specific impulse by an amount which will usually be less than 5%. This is because in a practical motor sufficient time is probably not available during the expansion process for attaining chemical and physical equilibrium; assumptions of equilibrium, therefore, will not be valid. (See, for example, reference 4).

(a) For a weapon of the size of the V.2, a 5% improvement in the measured specific impulse would enable the amount of propellant carried to be reduced from 18000 lb to 17520 lb for the same filled weight of the weapon and velocity at "all-burnt". This means that the weight of the warhead could be increased from about 2200 lb to 2680 lb, an increase of nearly 22%.

(b) For R.T.V.2 as first assessed[5] a 5% improvement in the measured specific impulse of the propellants would permit an increase in weight of the warhead from 150 lb to about 193 lb, on the assumption that the filled weight of the projectile remains the same and no important structural alterations are necessary. If the proximity fuze is assumed to be capable of operating at any distance this should, according to guarded expert opinion, result in an increase of lethality of the order of 13% to 18%.

(c) The range of a rocket missile travelling in vacuo, to which the case of a large rocket missile travelling most of its path in a rarefied atmosphere is a rough approximation, is proportional to the square of the specific impulse so that a 5% increase in specific impulse is equivalent to approximately a 10% increase in range.

The above examples illustrate the gain in performance of rockets which can be expected from improving the combustion of the propellant. The other main direction in which combustion research may effect a useful improvement is in reducing the size of the combustion chamber. For example, if the value of $L^* = \dfrac{\text{combustion chamber volume}}{\text{throat area}}$ in a weapon the size of R.T.V.2 could be reduced from 90 inches to 45 inches the saving in weight would be of the order of 1.5% on the filled projectile. This saving is important; it means that for the same weight of filled weapon a projectile with L^* = 45 inches can carry nearly 3% more propellant or an 18% larger warhead. Saving in weight on the combustion chamber is sometimes also important from the point of view of getting the correct weight distribution in the projectile. This aspect has assumed importance in rocket propelled model aircraft where too heavy a combustion chamber at the rear of the model has necessitated the use of ballast in the nose.

Another important advantage of reducing the volume of the combustion chamber, quite apart from the saving in weight, is that normally (although not necessarily) the surface of the chamber exposed to the hot gases will also be smaller. Unless the change in shape has led to increased gas velocities over the surface, e.g. by making the chamber narrower, this in turn means that the total heat transfer to the walls and nozzle of the chamber is reduced. This aspect may be of particular importance as hotter and hotter propellants are brought into use, for it is believed already that with rockets working at 300 lb/sq in. the limit for regenerative cooling has nearly been reached with existing propellants. This limit is fixed by the thermal capacity of the propellants and it would appear that the only way to apply regenerative cooling to motors working at higher temperatures would be by cutting down the total heat transfer to the nozzle and walls.

3 Factors affecting combustion in rocket motors

3.1 Bipropellant systems using propellants which do not self-ignite

3.11 Introduction

In all conventional systems of this type the propellants enter

the combustion chamber in the liquid form through nozzles which are designed to bring about the early break-up of the propellants into drops which usually range in size from 5 to 200 μ. The methods of injection used, in general, bring about only macroscopic mixing and ensure that there are no large sections of the chamber where one propellant is greatly in excess of the other, unless this is arranged intentionally as when excess of fuel is kept near the walls so as to protect them from being attacked by oxidant. When the droplets have evaporated and reacted as far as possible, it is left to turbulence and diffusion to bring about homogeneous mixing. The processes which take place between the injection of the liquid propellants and the emergence of the hot products of reaction are many and complex and in order to get an idea of the relative importance of each it is desirable to study them individually. They can be divided broadly into processes of atomization, evaporation, chemical reaction and mixing of the products accompanied to a varying extent by further chemical reactions. These processes are not independent of each other and they may well all be occurring in the same place at the same time. For example, a fuel may be evaporating and burning while it is still in the process of atomization, and the products of combustion formed may be mixing with others in the neighbourhood. There may be times when the spray atomizes and the droplets are evaporated by hot but unreactive gases in the neighbourhood and then later react with oxidant in the vapour phase. These processes and various others may all occur to a greater or smaller extent in different parts of the same motor, and their relative importance will vary with different fuel combinations. If the complete combustion process is to be understood the mechanism of each possible step and the factors which control it must be studied.

3.12 Atomization

The process of atomization, owing to its wide use in many fields of human activity has received considerable study (for bibliography see reference 6) and although it is not yet by any means completely understood, more is known about it than most of the other processes which take place in a rocket motor. There is, however, relatively little information on the impinging jet method of atomization especially in relation to the subsequent distribution of the two impinging liquids and any emulsification which may be produced. More work is also required on the effect of the density of the gas into which the liquid is injected. The effect of drop size distribution on combustion in a gas turbine engine was examined theoretically by Probert[7] who concluded that for maximum efficiency with a given chamber size the spray should not only be fine, but the drop size should be as uniform as possible. This conclusion has also been reached by Adams[6] for rocket motors, although its final validity must await experimental proof.

3.13 Combustion of droplets

The combustion of droplets of fuel in an oxidizing atmosphere is a process which, although it is of frequent occurrence in various branches of engineering, has been very little studied. It is, of course, a complex process involving simultaneous heat transfer, mass transfer by means of evaporation and chemical reaction. Even the separate processes of heat and mass transfer under varying conditions are too complex for adequate theoretical treatment although with the aid of dimensional analysis and experiment useful relationships for the heat transfer to spheres and for the evaporation of droplets in a flowing gas have been obtained by Kramers[8] and Frössling[9] respectively.

Their results, however, have only been checked at atmospheric pressure. The experiments of Topps[10] on the evaporation of falling hydrocarbon drops and of Godsave[11] on the combustion of stationary drops were likewise carried out at atmospheric pressure. In view of the difficulty of treating theoretically even the individual steps in the process of combustion of a drop under a wide variety of conditions of gas flow, pressure, etc., it appears clear that the combustion of droplets would best be studied experimentally and some work of this nature is in progress at R.P.D. Two lines of attack suggested themselves initially. They are (a) the study of stationary flames formed by a suspension of droplets in air or other oxidizing atmosphere, (b) the study of the combustion of individual droplets. The results of (a) have already been reported[12], but they are of somewhat limited applicability because such flames can only be formed with very small droplets and it is not easy to adapt the technique of study to higher pressures. Work on (b) is now in hand and considerable progress has been made in overcoming some of the experimental difficulties in making, manipulating and igniting small drops.

3.14 Mixing processes following on injection

The mixing processes which follow reaction in the flame region inside an actual rocket motor are not well understood. As already stated, the normal methods of injection lead only to macroscopic mixing and it is left to turbulence and diffusion to bring about the homogeneous mixing of the products which is necessary for complete reaction. Unfortunately this process is not always as rapid as could be desired and the burner pattern can sometimes be traced by chemical analysis throughout the length of the chamber and sometimes even into the exhaust jet[13,14]. It is reasonably certain that a considerable degree of turbulence is generated in the combustion zone, but as uniform mixing of the products of combustion is frequently not achieved the scale of turbulence would appear to be not very large. If large scale turbulence does exist in these cases then it must be of such a low intensity that it does not have time to produce much mixing during the passage of the gases through the combustion chamber; the conditions of rapidly accelerating flow such as exist in the nozzle and its approaches are known to be very unfavourable to the persistence of turbulence. The mixing of gases by eddy diffusion is important in a number of branches of engineering including the combustion system of the gas turbine, but although it has received a good deal of study at atmospheric pressure (see for example references 15, 16 and 17) there is little information on eddy diffusion at rocket motor pressures.

3.15 Time of stay in combustion chamber

It is obvious that the above processes of atomization, evaporation, chemical reaction and mixing take time, and the time of stay (in the combustion chamber) is sometimes defined by the equation:

$$t_s = \frac{V_c}{wV_1}$$

where V_c is the chamber volume, V_1 the mean specific volume of the propellant gases measured at the chamber temperature and pressure and w the mass flow of the propellant per second. It is apparent, however, that t_s only approximates to the real time of stay when the density of loading of the system (ratio of the volume of liquid propellant in chamber to the volume of chamber) is small, i.e. when the time taken for evaporation of the propellant is very short. A

more frequently used parameter is $L^* = \frac{V_c}{A_t}$, where L^* is the characteristic chamber length and A_t the area of the throat. For propellants of similar specific impulse and working at the same pressure, L^* and t_s are approximately proportional to each other since $A_t \propto wV_1$ approximately. L^* is a very useful parameter for the engineer, who is interested in burning the propellants in the smallest possible volume. Even if t_s or L^* is assumed to give a measure of the time taken for the overall combustion process it is only an average time, and some of the propellant may spend a much longer or shorter period in the combustion chamber than the rest. This is made obvious by considering an extreme case, such as a combustion chamber many times as wide as it is long, where much of the gaseous products of combustion may be practically stagnant. Before it is possible to design a combustion chamber on more or less rational grounds, it is necessary to have a knowledge of the flow conditions in chambers of various shapes.

3.16 Flow conditions in the combustion chamber and their study by means of models

The flow conditions desirable for one propellant system may be very different from those required for another. For example, in a system which requires a large amount of heat to raise it to the ignition temperature (e.g. ammonium nitrate/fuel/ water monopropellants) it is probably desirable that a considerable proportion of the products should circulate back to the burner head before making their escape through the venturi; the minimum amount of recirculation, however, is probably desirable with relatively hot and heat sensitive propellants such as methyl nitrate. The question of the amount of recirculation which can occur in a rocket motor is very controversial. It is probable that not much recirculation occurs in most of the rocket motors using conventional bipropellants. The main evidence for this is the persistance of flow patterns. It seems possible, however, that some recirculation may occur in combustion chambers of suitable shape; the droplets entering the combustion chamber from the burner head will be slowed up by friction and the surrounding gases will be set in motion in the direction of the venturi. Other gases would tend to move inwards near the burner head and recirculation would be set up. A spherical combustion chamber would be expected to be more favourable to recirculation than a long cylindrical one where the flame front is the full width of the chamber. If there is no recirculation, then since the incoming propellants will lose some momentum before burning there should be a slight pressure gradient from the flame front to the burner head. If recirculation is not necessary in order to maintain combustion then it is probably undesirable, as it would be expected to increase heat transfer to the walls. The problem arises, therefore, of finding the best means of investigating the flow processes in a combustion chamber. Observations on an actual rocket motor would be difficult, because even if the chamber were fitted with transparent windows the three dimensional nature of the flow would render direct observation of the complete flow almost impossible. It might, however, be possible to determine the direction and velocity of flow near the walls (e.g. by means of smoke or tracer particles) and this would establish the existence or otherwise of recirculation. Some observations have been made in America with small rockets made of glass, quartz or some plastic material which lasts just long enough to take a few cine photographs. The most recent work[18] has been carried out with liquid oxygen/petrol in a two dimensional rocket motor with transparent parallel walls of methyl methacrylate polymer. While the use of a low melting point plastic material avoids incandescence of the walls which may obscure the combustion pattern,

the chamber is continually melting away during its short life and the combustion conditions are therefore also changing. The experiments did, however, allow a few useful qualitative observations to be made. One is then led to consider whether it would be possible to study the flow with some simpler fluid than the rather complex mixture of liquids and gases which exists in a rocket motor. Such substitutions are fairly common in other fields and can be shown to be permissible by dimensional analysis of the problem. For example in some aerodynamical problems it is possible to substitute water for air, and Thring[19] has adopted similar methods in some of his work on blast furnaces carried out by means of models. Furthermore, the analogy between gas flow and liquid flow with a free surface[20] has been applied to the study of the flow conditions in and around a ram-jet[21]. A study of the rocket motor problem, however, shows that there would initially be no justification for making such a substitution. The difficulty arises from the fact that in a rocket motor the propellants enter as liquids and emerge after chemical reaction as gases. To simulate this state of affairs with a single liquid it would have to undergo a change of state requiring a great deal of heat. The simplest way of supplying this heat is by chemical reaction as in a rocket motor. The choice of suitable material, however, for constructing the model would be greatly simplified if it could be run on a propellant system working at a comparatively low temperature, and also if possible at a lower pressure than is usual in rocket motors. Now the flow pattern in a rocket or its simulating model would be expected to depend largely on the density change which occurs at the liquid/gas transition and on the place where it occurs and it is desirable to ensure that these are as nearly as possible the same in both the rocket and the model. Since the volume of the liquid is small and can be neglected, it is, therefore, sufficient if the gases in the rocket and model have the same density. If any effects due to dissociation at high temperatures are neglected and it is assumed that the molecular weight remains the same this is achieved if the ratio T/P (where T is the absolute temperature) is the same in rocket and model, which is rather convenient. It means that a model running at a relatively low temperature should also run at a low pressure. It is only necessary to ensure that the running pressure is above the critical pressure at which the flow at the throat becomes sonic. HTP and calcium or sodium permanganate suggest themselves as a low temperature propellant system suitable for the purpose. To simplify the study it would be desirable to pay some attention to the injector so as to confine the liquid to gas transition to as narrow a zone as possible. There should, however, be little difficulty with the above system as reaction in the liquid phase is very rapid. The above system will give rise to a small amount of solid, but if this proves troublesome HTP/hydrazine hydrate could probably be used as J.Diederichsen has shown that it is possible to run this system at oxidant/fuel ratios corresponding to very low temperatures.

The use of a low temperature system would permit the model to be made of heat resisting glass or quartz and the question then arises how the flow in a transparent three dimensional model may be studied. A two dimensional model with its opposite plane surfaces transparent is attractive, but it does not give a true representation of flow in a three-dimensional rocket, as the flow in such a rocket cannot be built up by combining the flows from a number of two dimensional models. It was originally intended to use a quasi-three dimensional model of the type shown in Fig.1 which it was thought would give a flow pattern which could be made visible by tracer particles and which would be closely similar to that in the actual rocket, if it is assumed that there is no large scale movement around the longitudinal axis of the

motor and the radial bounding walls do not have too great an effect. If these assumptions are valid it will be seen that it is possible to build up the flow in a complete rocket from that obtained with a single model. Fig.1(b) is a somewhat less ideal version which would probably be easier to construct. Exploratory experiments with both two dimensional and quasi-three dimensional models using a suspension of aluminium in water have, however, shown that boundary layer effects are important and make interpretation of the results unreliable. A much more attractive method is to use a transparent three dimensional model and adopt the method described by Nicholson[22] for studying the mechanism of flame stabilization in the wakes of bluff bodies. Briefly the method consists in suspending fine aluminium powder in the gas stream and illuminating it by a narrow beam of light; only the particles in the plane of the beam are illuminated and can be photographed by scattered light. Nicholson's work was carried out in a duct having a square cross-section, but exploratory experiments at R.P.D. suggest that it can be applied to a circular cross-section. In the model rocket motor it is intended to include the aluminium powder (or other suitable solid) in one or other (or both) of the propellants. The HTP/sodium permanganate system would indeed provide its own solid, but it may not be in a suitable form for visualisation or photography.

3.2 Bipropellant systems with premixing

Some work has been done at R.P.D. and also in America on rocket motors in which two immiscible propellants are formed into an emulsion in a specially designed nozzle immediately before injection into the combustion chamber. The reasons advanced in support of this method of injection are firstly that less space is required to mix propellants in the liquid phase than in the gas phase, and secondly, since each droplet of the resulting emulsion should contain the correct proportion of intimately mixed fuel and oxidant it was hoped that such droplets would burn more or less explosively; the net result should be a reduction in the value of L^*. Early work on the combustion of single droplets of HTP/kerosene emulsion showed that fairly large drops (ca 1000 - 1500μ) do not burn very rapidly when suspended on a wire and ignited. More recent experiments in which smaller droplets (ca 500μ) were injected into hot air indicate, however, that under these conditions combustion is much more rapid than with kerosene alone. Further experiments are in progress. Work on nitric acid/kerosene motors with premixing nozzles has not gone far enough to draw any conclusions about the possible reduction of L^* as compared with conventional injection but the indications were that combustion was occurring very close to the injector. This work has been temporarily suspended owing to frequent explosions especially during starting. The similarity between this system and one using a monopropellant is obvious.

3.3 Bipropellant systems with self-igniting propellants

As the combustion processes in systems of this type will depend considerably on the speed of reaction in the liquid phase, it is not possible to make general statements about them. With nitric acid systems, e.g. WFNA/WAF1, reaction in the liquid phase is very rapid, the liquids boil almost immediately on impact* and combustion is completed in the gas phase. With hydrogen peroxide systems such as

* Footnote: Most of the observations on impinging jets of nitric acid and self-igniting fuel have been made at atmospheric pressure and are, therefore, only strictly applicable to the ignition process. At rocket motor pressures the boiling points of the liquids will be raised, but it is not thought that this will seriously affect the validity of the above statement.

HTP/C-fuel reaction in the liquid phase is slow by comparison and much of the propellants will reach the flame zone in the form of droplets. The degree of mixing of the propellants before break-up will depend on exactly how they are brought together. In some systems it is possible that a large proportion of the droplets formed on impingement may consist of unmixed propellants and then, once ignition has started, the combustion processes will be very similar to those in a rocket using non self-igniting fuels. Little is known about the degree of mixing before break-up produced by the various impinging systems used in rocket motors, but it is intended to carry out some experiments to get more information on this point.

The ignition process, which is fundamentally different in self-igniting and non self-igniting systems, is discussed separately.

3.4 Monopropellant Systems

In monopropellant systems the problem of mixing propellant and oxidant does not arise, neither should there be any mixing problem following combustion for the products should be of uniform composition across the whole section of the chamber. Furthermore the mode of combustion of conventional monopropellants is similar to that of solid propellants such as cordite which has received considerable study, so that some theoretical approach to the problem is possible as has been made by Adams[6], but the picture is still far from being complete. A somewhat puzzling factor about monopropellant combustion is that although no mixing processes are involved monopropellants invariably require chambers having L^* greater than that for bipropellant systems operating under similar conditions. The reason for this is not clear.

For fairly low temperature monopropellants a kinetic explanation may be plausible; for example the normal value of L^* required for running a motor on hydrazine at a chamber pressure of 20 atmospheres is 500 inches for the reaction

$$3N_2H_4 \longrightarrow 6NH_2 \longrightarrow 4NH_3+N_2 \longrightarrow 3N_2+6H_2$$

It is reported, however, that if a chamber with a smaller value of L^* is used the reaction does not go beyond the $4NH_3 + N_2$ stage and in consequence a somewhat higher specific impulse is obtained. (The reaction $4NH_3 \longrightarrow 2N_2 + 6H_2$ is endothermic and although the molecular weight decreases this is not enough to compensate for the fall in temperature, i.e. T/M is greater for the $4NH_3 + N_2$ than for the $3N_2 + 6H_2$ stage). For monopropellants such as D20 (dithekite 20) and nitromethane, however, which give specific impulses only a little lower than the conventional bipropellant systems and which operate at quite high chamber temperatures purely kinetic explanations are perhaps not altogether convincing. An alternative explanation which suggests itself is that the difference in L^* requirements may be due to a difference in the degree of turbulence in the combustion zones of the two systems; the chemical and physical inhomogeneity of the combustion zone in a bipropellant motor favours turbulence whereas relatively little turbulence may exist in the combustion zone of a monopropellant motor. Since in both types of motor evaporation of the propellant is probably an important time consuming process and would be greatly speeded up by turbulent mixing of the incoming propellants with the products of combustion, it may be that the different degrees of turbulence in the two systems are largely responsible for the difference in the values of L^* required. Turbulence may, of course, also speed

up the chemical reactions in the system.

These speculations on the reasons for the large value of L* required by all monopropellant motors could be tested experimentally by means of a composite monopropellant whose ingredients could also be used in a corresponding bipropellant system. For example dithekite 20 consists of 57.5 parts of nitric acid, 22.5 parts of nitrobenzene and 20 parts of water; its L* requirement as a monopropellant is known, but it could also be fired as a bipropellant with aqueous nitric acid as the oxidant and nitrobenzene as the fuel. If we ignore the possibility of some reaction in the liquid phase during evaporation in the case of the monopropellant system, then the chemical kinetics should be substantially the same when it is fired as a bipropellant system and any large difference in the L* requirement would be mainly attributable to differences in the mixing processes in the combustion and precombustion zones. It would, of course, be necessary to use the same or similar injectors for both the monopropellant and bipropellant systems, but this should be possible, e.g. with impinging jets. A similar experiment could be carried out using two rocket motors, one with a conventional injector and the other with a premixing nozzle which produces what is substantially a monopropellant.

The large values of L* required for monopropellant motors are an important factor which militates against their use and it was in fact the need to reduce the value of L* of the monopropellant motor under development at R.P.D. which encouraged the initiation of the rocket model studies already described.

The chemical similarity between many solid propellants and liquid monopropellants has already been pointed out. A detailed comparison between the two types of motor is, however, somewhat complex and will not be made here. An obvious difference is that in a solid propellant rocket the primary flame front is fixed by the geometry and position of the charge and in most motors there is a considerable gas velocity over the greater part of its surface. A further important point of difference is that until melting and/or evaporation and decomposition has occurred in a solid propellant motor the propellant is fixed and must remain in the chamber; in a monopropellant motor (and also in bipropellant motors), however, the motion of small droplets of propellant is mainly controlled by the gas flow, and if they do not evaporate sufficiently rapidly they may be carried out of the rocket in the gas stream with a consequent loss in performance.

4 Ignition in rocket motors

4.1 Ignition in rocket motors using propellants which do not self-ignite

Even an understanding of the process of ignition of quiescent gas mixtures is difficult and under the much more complex conditions prevailing in a rocket motor a rational scientific treatment of the problem is at present quite impossible. There are, however, one or two broad principles which can probably be applied. It has been found in igniting atomized paraffin/air mixtures in a fast flowing stream such as occurs in the ram jet that the rate of input of heat from the igniter had to be increased as the air speed increased. This is what might be expected from an elementary consideration of the problem; if we imagine the hot flame gases being rapidly diluted with the surrounding mixture then the resultant temperature of the mixture will be below its ignition temperature. Even if a flame starts to propagate in the streaming suspension of droplets the flame

surface might still be broken up and cooled before it propagates very far. This could be caused, for example, by turbulence or by the passage of large fuel droplets through the surface[12]. The same kind of considerations will apply to a rocket motor, although here nearly all the propellant (fuel and oxidant in a bipropellant system) will be in the form of liquid droplets. Reaction can only occur in the vapour phase and since most of the liquids used have a considerable latent heat of evaporation they will exert a considerable cooling effect on any flame which they pass through at high rates of flow.

The ignition problems needs increasing attention as the size of the rocket increases. If the igniter is situated at a certain point in the motor then the time taken for the flame to travel from that point to every other point in the chamber will obviously increase with the size of the motor. For an igniter situated at the centre of a spherical combustion chamber we can assume that this time is approximately proportional to the radius. Now suppose that the rocket is scaled up in size so that the thrust is increased eight times, but the value of L^* remains the same. The radius of the chamber will be increased twofold and also the time for complete ignition, so that with an eightfold increase in flow rate about sixteen times as much propellant will have passed into the chamber during the ignition period. If the weight of this propellant exceeds the weight of propellants plus products which would normally be present during steady running, there is likely to be a pressure surge above the working pressure of the rocket. If this surge is roughly proportional to quantity of propellant/volume of chamber then it will be twice as great with the larger rocket. Although the above discussion has been greatly simplified it seems probable that the ignition problem is likely to be of greater importance as the size of the rocket is increased. For large rockets it may be necessary to use several igniters to reduce the ignition interval or else to have a rotating igniter of the catherine wheel type such as was used for ignition of the V.2. There is at present little knowledge of the velocity with which flame travels from the source of ignition through the propellant spray, but such knowledge is clearly desirable. This is not very easy to obtain under rocket motor conditions, but some information should be obtainable by careful examination of the build up of pressure after ignition. It would be desirable to use a point source of ignition for this purpose; a high energy spark may be sufficient for some systems, e.g. those using liquid oxygen, and this would also give the time of ignition very accurately. It may also be useful to examine the rate at which flame is propagated through the propellant spray at atmospheric pressure, especially if a knowledge of the effect of pressure on the flame speed could be obtained from independent experiments.

4.2 Ignition in rocket motors using self-igniting fuels

Although the delay associated with the ignition of self-igniting fuels has received a good deal of study in the laboratory, particularly with the twin-jet apparatus[23,24,25,26] there are many points concerning ignition under rocket motor conditions which are not clear. The liquid velocities in the twin jet apparatus are usually less than 10 ft/sec, the difference in velocity between the two streams is only a few ft/sec, and the two streams of liquid on meeting run together in a single stream until ignition occurs. Under rocket motor conditions, however, the liquid velocities commonly exceed 100 ft/sec, and the difference in the velocities of the two streams is correspondingly greater; the two streams do not form after impact a single stream

which persists until ignition occurs and little is known about the degree of mixing which takes placed before break-up.

Even if the high liquid velocities did not cause break-up on impact the method of injection is usually such as to prevent the liquid streams remaining together till ignition. For example, in the individual injection nozzles of the Walter 109/509 motor[27] the propellants enter from two concentric swirl orifices and form expanding cones which impinge and break-up before ignition occurs. The delay in ignition and ultimate failure to ignite at altitude has been studied in the laboratory[24] and work is now being carried out at R.P.D. with a small motor running in a decompression chamber.

5 Conclusions

It is concluded that the improvements in rocket performance which may result from combustion research are well worth the effort expended. There are a number of directions in which further knowledge is required and the following are considered to be among the more important:-

1. The degree of mixing and pattern of dispersion of droplets produced by impinging jets or cones of both self-igniting and non self-igniting fuels.

2. The study of the combustion of droplets of various rocket propellants in atmospheres of the type which may exist in rocket motors with particular reference to the effect of the size of the droplet and the combustion pressure. This work is in progress at R.P.D.

3. A study of the flow conditions in rocket motors of various shapes with special reference to the region near the flame front and injector. It may be possible to do this by means of models working at low temperature and pressure. Work on these lines has been initiated at R.P.D.

4. Study of the rates of propagation of flame through a cloud of atomized propellants such as is produced by a rocket injector.

5. Determination of the L^* requirements for a composite monopropellant when operated both as a monopropellant and as a bipropellant system.

It will be necessary at all stages of the work to compare and correlate results obtained in the laboratory with those obtained in rocket motors on the test bed.

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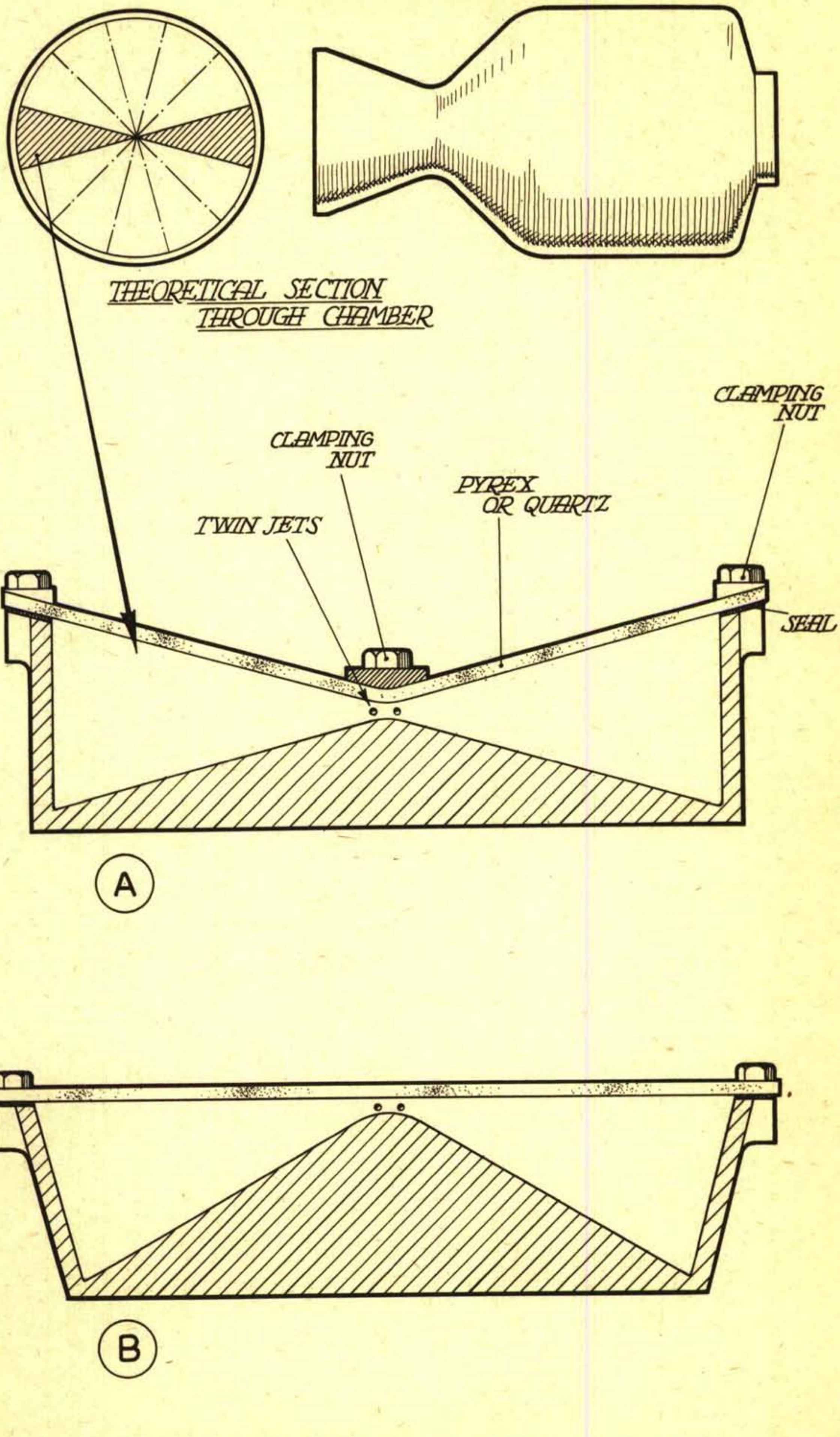

FIG. 1. QUASI THREE DIMENSIONAL MODELS FOR
STUDY OF FLOW IN COMBUSTION CHAMBERS

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